

# VEGETATION, FIRE AND ABORIGINAL IMPACT ON THE MID-HOLOCENE MOIRA MARSHES, NEW SOUTH WALES, AUSTRALIA

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Analysis of palynological and sedimentological data from floodplain and lake sediments 2-5 m below the modern surface of the Moira Marshes enabled reconstruction of the vegetation, fire history and river activity and assessment of the role of climate and people on this landscape. Saturated floodplain conditions existed until ~4,000 years BP. A lake then formed and the Murray River increasingly influenced the site, dominating floodplain hydrology and local vegetation. On the Riverine Plains were Casuarinaceae/*Eucalyptus* semi-arid open woodlands, and extensive areas of saltbush shrubland. Increasing regional aridity culminated in soil salinization. At higher elevations temperatures were lower, and effective precipitation higher, than today. Wetland vegetation expanded as the lake infilled and floodplain swamplands developed, enabling the establishment of the modern *Eucalyptus camaldulensis* forest 3,000 to 2,000 years ago. Regional fires were initially infrequent but as wetland resources developed local fire frequency increased altering the vegetation structure and composition. This change is best related to people utilizing a now resource-rich landscape from ~4,000 years ago. Occupation was partially controlled by environmental variability; but land-management by fire created and maintained important woodland resources.

**Key words:** Moira Marshes, mid-Holocene, vegetation, fire, climate, human impact.

THE Barmah-Millewa Forest and Moira Marshes are significant wetlands protected under the 1974 JAMBA, 1986 CAMBA and RAMSAR agreements. In 2002 the River Red Gum Forests were given iconic status under the Murray-Darling Basin Commission 'Living Murray Initiative' as an important and enduring vegetation type (MDBC 2002). Despite these initiatives we know very little of the Holocene Murray River environment or when these forests were established.

The history and characteristics of the Quaternary palaeo-channels of the Riverine Plains are well-studied and have been related to pluvial and arid climatic cycles (Bowler and Harford 1963; Schumm 1969; Page et al. 1991; Ogden et al. 2001) but, the vegetation history and the roles of climate, fire and people in shaping this landscape is largely unknown. Information on vegetation dynamics and landscape processes can only be derived from palaeoecological records in which increased charcoal concentrations are often attributed to anthropogenic activity on a regional scale (Singh and Geissler 1985; Kershaw 1986). Different spatial scales of analysis are required to identify localised human activities from those used to reconstruct regional landscape dynamics associated with chang-

ing climate (Jacobson and Bradshaw 1981; Birks and Birks 1988). Small-scale cultural activity is difficult to identify in Australian records, not only because of the long period of low intensity human occupation but also because of long-term climatic variability that has dominated vegetation change. However, the use of specific indicator species or the ecology of plants present in the pollen record can help determine whether the direction of change is climate-dominated or one maintained by people.

People have been an integral part of the Murray River landscape for at least 18,000 years (Thorne and Macumber 1972; Pardoe 1998; Stone and Cupper 2003) where abundant resources along the river and in its hinterland supported a large population (Bonhomme 1990; Pardoe 1994). Shell mounds, middens, large ovens, scar trees and burials in the Barmah-Millewa region record 3,000 years of occupation by a large population comprising three tribal groups related by language; Joti Joti (Yota Yota), Kwat Kwat and Pangerang (Curr 1883; Bonhomme 1990; Clark 1990). Historical accounts indicate the population had declined considerably just before the arrival of Europeans in the region (Curr 1883; Sturt 1899).

In this study sedimentological, palynological and charcoal evidence from floodplain and lake

sediments from the Moira Marshes, New South Wales, have been used to investigate the mid-to-late-Holocene regional and local vegetation, changing fire regimes and river dynamics. The impacts of climate and people on the landscape of the Moira Marshes are also assessed.

## SITE DESCRIPTION

### *Location*

From Tocumwal to Echuca the Murray River floodplain is several kilometres wide, and flat with a slope of 1:50,000 (Fig. 1A) whilst the presence of numerous palaeo-channels attest to changing Quaternary fluvial activity (Currey and Dole 1978). Extending for 60 km between Deniliquin and Echuca is The Cadell Fault; a 14 m high west-sloping escarpment. Movement along this fault disrupted the drainage system across the region and has, since then, controlled the hydrology and ecology of the

region (Rutherford 1990). The Barmah-Millewa River Red Gum and wetland complex have formed on the deltaic eastern side of the fault between Tocumwal, Deniliquin and Echuca. Across this region many anabranching distributary creeks leave the Murray River and dissipate on the floodplain as shallow lakes and wetlands. They return floodwaters to the Murray River to the south, via the Barmah and Moira Lakes, and to the north via the Edward River and the Gulpa and Bullatale Creeks (Bren 1988; Lawrence 1988). At Pienie Point the Murray River turns south and flows along the low eastern edge of the Cadell Tilt-block through a narrow and relatively straight reach called 'The Choke' (Harris 1938).

The Barmah and Millewa Forest and wetland landscape (part of which is shown in Fig. 1B) is a complex of lacustrine, modern and palaeo- stream channels, aeolian lunettes, river margin source bordering dunes and deltaic features (Harris 1938; Bowler and Harford 1966). The chronology and the hydrological and climatic controls on these land-



Fig. 1A. Regional map showing the location of sites mentioned in the text and the placement of pollen traps within Barmah Forest (\*). Inset is area covered by 1B. 1. Pienie point; 2. Moira Marshes; 3. Barmah Sand Hill



Fig. 1B. Map of Moira Marshes and the location of the study site. Map adapted from the MDBIC LIDAR DEM data at 10 m spatial resolution.

scap features are poorly understood. The floodplain is composed of silty-clays with lenses of sand, presumably related to anabranching channels. The Moira Marshes are part of this forest and wetland system (Figs. 1A & B) occupying 1,500 ha between the Cadell Tilt Block and the 'Barmah Choke' (Harris 1938; Currey 1978). The study site is adjacent to the Murray River at the southern margin of the modern Moira Lake that occupies the floor of a larger palaeo-lake (Fig. 1B). The Murray River has built a digitate delta along this section of the channel (Bren 1988).

**Chronology of floodplain evolution.** Harris (1938) believed there have been several periods of movement on the Cadell Fault and recent dating by Page and Nanson (1991) suggests movement began approximately 60,000 years ago. It is generally agreed that movement disrupted the previously westward flowing Murray River between 30,000 and 20,000 years ago and has left numerous abandoned sections of palaeo-river channels of different ages on the landscape. The issue of the early movement on the fault and the timing of any subsequent movement still needs to be resolved.

The disruption to the Murray River channel resulted in a diversion of the Murray River round the northern end of the fault via Gulpa Creek and, at the southern end Lake Kanyapella formed. A lake also formed on the low, upstream side of the fault. The strandline for this lake can be seen in Fig. 1B extending north from Buck's Sandhill and crossing the Murray River at Pienie Point (Currey and Dole 1978). Some time between 20,000 and 13,000 years ago the river broke through the Lake Kanyapella lunette (Barmah Sandhill), eventually draining the lake (Bowler and Harford 1966). Eventually, the Murray River breached the lunette at Pienie Point and flowed south across the Moira Lake floor building a digitate delta of clay, silt and sand sediments that separates the Barmah and Moira Lakes. Until a detailed chronology is developed for the region the actual ages of many of these events and the effect of the floodplain hydrology remain uncertain. For more detailed information on the geomorphology of the region see the paper by Rutherford and Kenyon in this volume.

### Climate

The region has a Mediterranean climate of winter rainfall and hot summers. Average annual temperatures are relatively stable at 13–15°C (Dexter 1978). Annual evaporation of 1400 mm exceeds annual precipitation of approximately 400 mm. The *Eucalyptus camaldulensis* forests and wetland communities rely on sufficient precipitation and snow fall in the eastern highlands to provide annual winter/spring flooding to balance this rainfall deficit (Dexter 1978; Cuddy et al. 1993).

### Vegetation

The vegetation of the Murray River corridor and that of the Riverine Plains have been highly modified by grazing, logging, agriculture and changed fire regimes since the 1840s (Lunt 2002). Historically, the Moira Marshes were a complex lake and wetland system consisting of the Moira and Barmah Lakes and a series of lagoons and treeless swamps dominated by tall, impenetrable reed beds (*Phragmites australis*) through which the Murray River flowed (Curr 1883; Coulson 1979). Within the reed beds were small elevated strips of land covered in pigface (*Mesembryanthemum aequilaterale*) (Coul-

son 1979). Other wetland vegetation included bulrush (*Typha* spp.), spike rushes (*Eleocharis sphacelata* and *Eleocharis acuta*), nardoo (*Marsilea drummondii*), milfoil (*Myriophyllum crispatum*), water ribbons (*Triglochin* spp.), *Juncus* spp. and *Azolla filiculoides* (Chesterfield 1986). Open Moira grass (*Pseudoraphis spinescens*) plains between the reed beds were a feature of the region (Curr 1883; Chesterfield 1986). The Moira Marshes are now surrounded by river red gum (*Eucalyptus camaldulensis*) forests that also grow along the banks of the Murray River in this area. Due to changes in hydrology that are related to river regulation, the lakes are now fringed with giant rush (*Juncus ingens*) that, along with *Eucalyptus camaldulensis*, is invading the grass plains.

*Callitris glaucophylla*, *C. pressei*, *Exocarpos* spp., Myrtaceous shrubs, *Banksia*, *Acacia* spp. and *Allocasuarina leulmannii* grew on the drier sandy rises within the forests and on the sandy soils of the Riverine Plains. In the 1840s, to the west of Deniliquin, were vast areas of saltbush shrubland consisting of old man saltbush (*Atriplex nummularia*), bluebush (*Maireana aphylla*), goosefoot (*Chenopodium nitratum*) and hedge saltbush (*Rhagodia spinescens*). Also present in the region were semi-arid open woodlands and extensive grassy plains (Sargeant et al. 1979).

Late winter/early spring floods from snow-melt in the Eastern Highland inundated these swamps and lagoons. In summer, when river flow was low, the swamps dried and the lagoons became swamps. During periods of drought the whole area became a dry plain. This was still the case until the Hume Reservoir was commissioned in 1936. Winter flows are now retained in the reservoir and released during summer for downstream irrigation. These high summer flows often result in summer flooding of the forest (see Ladson and Chong, this issue). A levee bank was subsequently constructed along 'The Choke' and regulators installed on effluents to reduce summer flooding. These changes have profoundly affected the hydrology of the area (Bren et al. 1987).

## METHODS

Sediments between 2 m and 5 m below the modern surface were used for pollen, charcoal and sediment analyses. The vertical face of a trench dug into the Moira Marshes was sampled at 0.1 m intervals

between 2.1 m and 3 m and then at 0.5 m intervals to the base of the trench.

**Pollen analysis.** To determine the pollen rain produced by the modern forest, pollen traps were placed in differing vegetation communities within Barmah Forest and one trap was placed on the Barmah Sand Hill to collect the regional pollen rain (Fig. 1A). A 1 litre plastic bottle with a 4.5 cm diameter opening, covered with wire mesh to exclude insects, was positioned flush with the ground surface. Approximately 100 ml of glycerol and a small amount of Thymol were added to prevent pollen from oxidising and to inhibit fungal and algal growth (Hicks et al. 1996). Traps were in the field from May 1995 to May 1999 and changed at 3-monthly intervals.

Recent pollen data was also obtained from two sediment core surface samples; the Moira Grass (*Pseudoraphis spinescens*) Plain at Hut Lake and the tall *Eucalyptus camaldulensis* forest at Gower's Gate. For the Moira Marshes sediments, pollen was extracted from a 3 cm<sup>3</sup> sub-sample at each depth.

Sediment and pollen rain samples were processed using the KOH and acetolysis digestion method (Moore et al. 1991; Hicks et al. 1996) and the pollen isolated using sodium polytungstate (specific gravity 2). One *Lycopodium* spore tablet (12,542 spores per tablet) was added to each sample to calculate absolute pollen concentration (Jorgensen 1967). When excessive fungal contamination did occur in pollen trap samples they were treated, prior to acetolysis, with 1% sodium hypochlorite until the hyphae separated and freed the trapped pollen (Tauber 1974). Preparations were stored in a known volume of glycerol. A minimum of 200 dryland pollen grains was counted, from aliquots of known volume, at x600 magnification, using an Olympus binocular microscope. For the sediment samples, absolute pollen concentrations and the relative percentage of the dryland pollen sum were calculated for selected pollen taxa. For the pollen rain, average influx over the four years (grains cm<sup>-2</sup> yr<sup>-1</sup>) was calculated for each site using the formula:

$$\text{Pollen influx (grains cm}^{-2} \text{ year}^{-1}) =$$

$$P_i \cdot (L_T/L_C) \cdot (T_A) \cdot (12/S_p) \cdot 1/4$$

where  $P_i$  (no. pollen grains of each taxon counted);  $L_T$  (Total number of *Lycopodium* spores added);  $L_C$  (*Lycopodium* spores counted);  $T_A$  (trap area in cm<sup>2</sup>) and  $S_p$  (sample period in months).

The results were graphed using Tiliagraph V2 (Grimm 1993).

*Eucalyptus*, Casuarinaceae and Chenopodiaceae pollen were separated on morphometric (size) criteria: *Eucalyptus* 15–18  $\mu\text{m}$  and  $>20 \mu\text{m}$  equatorial diameter; Casuarinaceae  $<28 \mu\text{m}$  and  $>28 \mu\text{m}$  equatorial diameter and; Chenopodiaceae 25  $\mu\text{m}$ , 20  $\mu\text{m}$  and 15–17  $\mu\text{m}$  diameter. Pollen for each taxon was identified as 'grains in good condition' and 'weathered grains' to determine the influence of aeolian and/or riverine transport to the site and local pollen preservation conditions.

**Charcoal analysis.** The regional fire history was determined from charcoal present in the pollen preparations and the charcoal area ( $\text{mm}^2 \text{cm}^{-3}$ ) was determined using the point-count method of Clark (1982), using 11 points per field and 200 fields of view. To identify fires immediately adjacent to the site, charcoal particles greater than 100  $\mu\text{m}$  (Clark 1988; McKenzie 1989) were counted, concentrations (no. particles  $\text{cm}^{-3}$ ) calculated, and the results graphed.

**Sediment analysis.** Magnetic susceptibility is a measure of the ferri-magnetic content of sediments and is used to identify changes to sediment influx at a site due to catchment erosion, land-use, forest fires and can help determine environmental conditions at the time of deposition (Thompson and Oldfield 1986; Gale and Hoare 1991; Caitecheon 1993). At each depth, sediment samples of 1  $\text{cm}^3$  were measured with a Bartington Magnetic Susceptibility Meter using the 0.1 range for weakly magnetic material. Electric conductivity (EC) was measured using a TPX digital pH meter to determine changes in groundwater at the site. Sub samples were mixed in distilled water in the ratio 1:5 (weight per volume), then shaken for 1.5 hours before measurements were taken (Leeper and Uren 1997). The bedload fraction ( $>63 \mu\text{m}$ ) of the sediments was quantified to determine the influence of the river on the site. Five gram sub-samples at each depth were dispersed using 5% tetra-sodium pyrophosphate ( $\text{Na}_4\text{P}_2\text{O}_7 \cdot 10\text{H}_2\text{O}$ ), then sieved at 1,000  $\mu\text{m}$  (coarse sand), 250  $\mu\text{m}$  (medium sand), 125  $\mu\text{m}$  (fine sand) and 63  $\mu\text{m}$  (very fine sand) and the results graphed as a percentage of bedload and as a percentage of total sample weight.

**Dates.** A single aliquot Optically Stimulated Luminescence (OSL) date was obtained from quartz sand grains at 2.7–2.9 m (pers. comm. T. Stone in prep.). Burnt Cyperaceae seeds (OZE895) between 2.1–2.3 m and beetle sclerite (OZE896) at 2.5 m were dated using the AMS  $^{14}\text{C}$  dating technique and the calibrated ages are reported

here with the permission of N. Porch, Monash University.

## RESULTS

### *Sedimentology*

Throughout, the sediments are predominantly silts and clays (Fig. 2). From 5.0 to 3.0 m they are grey/blue clays with a very low sand component (bedload) that increases from 0.7% to 1.7% of the total (Fig. 2). Magnetic susceptibility is very low in the two basal samples but increases considerably by 4.0 m. Between 4.0 and 2.7 m readings slowly decline. Loss-on-ignition (LOI) is constant at 5% (Fig. 2).

At 3.0 m a sudden change in the sediments to finely laminated, lacustrine clays and silts suggests these sediments were deposited under permanent lake conditions by an active river system and that bioturbation was minimal. An OSL date of 3,810  $\pm$  260 years was obtained from the base of these sediments (pers. comm. T. Stone in prep.) and a calibrated  $^{14}\text{C}$  AMS date (OZE896) of 4,840  $\pm$  40 years at 2.5 m. At 3.0 m bedload increases to 6% and by 2.7 m is 10% and, whilst the major constituent is very fine sand the coarser components also increase. Then, from 2.6 to 2.4 m the sand content decreases rapidly to less than 1% of the total with coarse and medium sands absent (Fig. 2). Maximum MS occurs at 2.6 m then suddenly declines to zero at 2.3 m. The LOI and EC curves show a similar rapid increase followed by declines and both have maximum values at 2.4 m.

Above 2.4 m laminations are absent and the presence of vertical desiccation cracks indicate prolonged periods when the surface was dry. Sediments between 2.1 and 2.3 m returned an AMS date (OZE895) of 3,290  $\pm$  90 years (N. Porch, pers. comm.). The bedload is variable in composition, but still only 4% of the total load. MS declines to zero at 2.3 m before increasing again.

There is some oxidation of small root channels and surface mottling throughout the profile that indicate wetting and drying cycles. This oxidation increases to 3.0 m, then again above 2.3 m. At 2.0 m the sediments are truncated by a layer of coarse sand overlain by floodplain silts and clays.

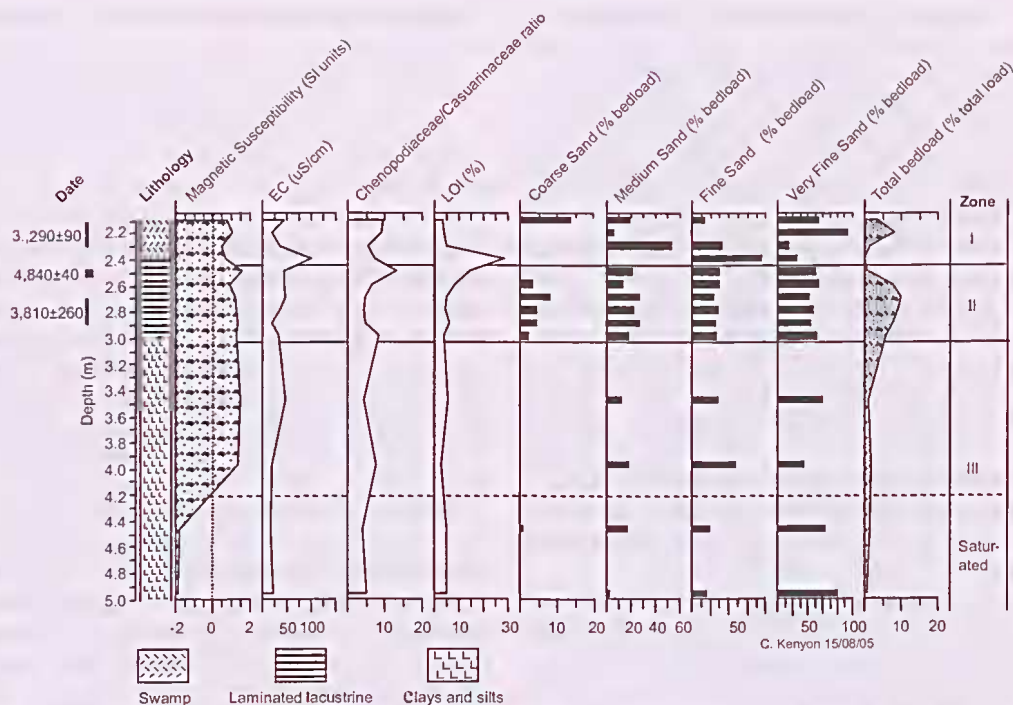


Fig. 2. Results of the Moira Marshes magnetic susceptibility (SI units), electrical conductivity, loss-on-ignition percentages and sediment particle size analysis. The sediment stratigraphy and dates are included. Chenopodiaceae/Casuarinaceae ratio is an indicator of regional soil salinization.

### Pollen analysis

**Modern pollen rain.** Due to high seasonal variability in pollen production the pollen rain data has been averaged over the four years (Table 1). Regionally, the arboreal, Poaceae and Asteraceae pollen percentages reflect the open nature of the agricultural landscape. Chenopodiaceae is less than 1% regionally and does not exceed 5% in the Barmah Forest pollen rain where it most likely represents *Einadia nutans*. Within the forest *Eucalyptus* (15–18  $\mu$ m) percentages reflect the *Eucalyptus comalduensis* forest structure, ranging from 12% in the open woodland to 32% in the tall forests with higher values on the box ridge. High Cupressaceae representation records the presence of *Callitris* plantations that have been planted south of the forest. Casuarinaceae pollen is wind dispersed and the constant but low representation and abundances at all sites are similar to the regional levels. Poaceae, Asteraceae and Cyperaceae dominate the forest understorey and are all well-represented. *Azolla* and *Myriophyllum* and palynomorph values are low at all sites and not present in the regional pollen spectrum.

**Surface samples.** The Barmah Forest surface samples reflect the vegetation community at each site (Table 1). *Eucalyptus* percentages are low and Poaceae percentages high at the grass plain. By comparison, at the forested site, *Eucalyptus* at ~35% is a similar value to the pollen trap data, and Poaceae and Cyperaceae, co-dominant in the understorey have equal representation. Only Casuarinaceae grains greater than 28  $\mu$ m are present and Chenopodiaceae representation is low. *Myriophyllum* percentages are very high and *Azolla* is higher than in the pollen traps.

**Moira Marshes sediments.** Pollen relative percentages and concentrations are shown in Figs. 3, 4. Zonation of the pollen diagrams is based on stratigraphic criteria with Zone III from 5.0 to 3.0 m; Zone II includes the laminated sediments between 3.0 and 2.5 m and; Zone I extends to 2.1 m where the sediments are not laminated.

Throughout this record the majority of Chenopodiaceae pollen grains are weathered indicating poor preservation conditions and/or long-distance aerial transport. Weathered *Eucalyptus* (15–18  $\mu$ m) grains, suggest pollen preservation conditions

Taxa	Core surface samples		Regional pollen rain	Forest pollen rain	
	Grass plain	Tall forest		Minimum	Maximum
<i>Eucalyptus</i> 15-18µm	2.7 (2461)	24.0 (800)	1.23 (5.00)	5.80 (12.28)	27.29 (78.17)
<i>Eucalyptus</i> 20 µm	3.3 (3077)	7.4 (250)	8.32 (33.33)	3.74 (35.43)	15.09 (84.18)
Total <i>Eucalyptus</i>	8.2	36.8	9.55 (33.3)	48.68 (88.71)	12.02 (48.82)
Cupressaceae	2.0 (1845)	0.9 (25)	1.81 (6.38)	5.32 (17.29)	9.36 (41.46)
Casuarinaeae <28 µm				0.30 (1.26)	1.12 (3.51)
Casuarinaeae >28 µm		2.5 (75)	1.55 (10.00)	0.57 (2.36)	1.47 (5.26)
Chenopodiaceae	1.5 (1384)	5.3 (150)	0.80 (3.87)	4.99 (41.67)	1.22 (5.86)
Poaceae	27.0 (22615)	24.6 (700)	10.08 (44.24)	30.13 (61.34)	13.57 (57.14)
Asteraceae	3.5 (2615)	14.9 (425)	10.66 (37.25)	3.06 (9.57)	7.77 (14.33)
Cyperaceae	9.5 (8923)	11.0 (150)		6.74 (21.05)	10.97 (30.10)
<i>Myriophyllum</i>	30.0 (34461)	32.3 (2800)		0.06 (0.36)	1.50 (6.35)
<i>Azolla</i>	3.0 (3846)	2.4 (175)		0.03 (0.38)	3.07 (9.91)
Palynomorphs		0.1 (1384)		0.15 (1.24)	1.08 (5.92)
Micro-charcoal area (mm <sup>2</sup> .cm <sup>-3</sup> )	33.5	24.3			
Charcoal particle (>100µm) cm <sup>-3</sup>	575.9	650.9			
Charcoal particle (>300µm) cm <sup>-3</sup>	9.8	124.8			

Table 1. Barmah Forest relative percentages of the dryland pollen sum and concentrations (...) for modern rain and surface samples, and micro and macro-charcoal for the surface samples. Seasonal data has been averaged for the period 1995-1999.

on the floodplain were poor or, pollen was transported to the site by the river or wind transported from the hinterland. Eroded palynomorphs were most likely river transported from upstream.

**Zone III:** In this zone there are few pollen grains; diversity is low and most grains are weathered. Taxa present include *Eucalyptus*, Casuarinaceae, Cupressaceae, Poaceae and Asteraceae, with Cyperaceae and *Persicaria/Polygonum* types representing wetland taxa (Figs 3, 4). The low number of grains hinders any interpretation of the regional or local vegetation.

**Zone II:** At the base of this zone pollen diversity increases, but after an initial increase herbaceous taxa diversity declines, except at 2.5 m where there is maximum diversity. The increase in pollen concentrations and diversity strongly suggest improved pollen preservation conditions rather than

vegetation change are responsible for the changes across this stratigraphic boundary.

Arboreal relative percentages of the dryland taxa are 20% - 25% with *Eucalyptus* and Casuarinaceae pollen both 30-40% of the total arboreal pollen and Cupressaceae (*Callitris*) under 5%. Many *Eucalyptus* pollen grains occur in groups of twos or threes indicating *Eucalyptus* was growing quite close to the site. However, approximately half of these are weathered suggesting that preservation conditions were still relatively poor or, pollen had been transported to the site. *Eucalyptus* relative percentages are variable but concentrations increase to 2.8 m indicating a local source for the pollen and; percentages and concentrations increase for both Casuarinaceae types indicating a regional source for the pollen. Poaceae percentages decline but

concentrations increase but Asteraceae concentrations increase whilst percentages remain constant.

Above 2.8 m *Eucalyptus* and Casuarinaceae percentages and concentrations decline with minimum levels at 2.5 m. *Eucalyptus* pollen declines from 15–7% of the dryland sum; but the >20 µm size range is consistently present in low numbers, whereas *Eucalyptus* (15–18 µm) concentrations and percentages are more variable and decline to 2%. Casuarinaceae also changes in composition with a rapid decline in pollen with an equatorial diameter <28 µm which is absent at 2.5 m, but Casuarinaceae (>28 µm), a smaller component of the vegetation, maintains consistent concentrations but representation is halved. Poaceae and Asteraceae concentrations increase but percentages are variable. Abundances for other herbaceous taxa decline rapidly and gradually become less important.

Pollen indicators for regional arid conditions - Cupressaceae, Sapindaceae and Gyrostemniaceae - all increase in abundance and representation but Myoporaceae decreases. Chenopodiaceae concentrations increase 10 times and relative percentages increase from 14% to 30% by 2.5 m, with approximately 15% of grains weathered: here it is the 25 µm size class that is dominant. The Chenopodiaceae/Casuarinaceae ratio (an indicator of soil salinization) increases from 2.6 m with maximum values at 2.5 m.

*Dicksonia* spores dominate indicators of riparian taxa with *Tasmannia*, *Acacia* and Lamiaceae present in low concentrations. Although, individual abundances are low, together they are 8% of the dryland pollen sum. The high proportion (50%) of weathered palynomorphs indicates they were transported from upstream. Above 2.7 m they decrease in abundance and, as a component of the vegetation, they are absent at 2.4 m.

Wetland taxa diversity is initially low at 3.0 m with their highest representation is 2.7 m but concentrations are at their highest between 2.6 and 2.4 m when percentages are low. *Polygonum* and *Persicaria* pollen types increase from 20% to 50% and, with Cyperaceae (20%), dominate the wetland taxa. Above 2.6 m, *Persicaria* and *Polygonum* decrease rapidly and remain low to the top of the profile. Although *Myriophyllum* and *Azolla* are poorly represented in the basal laminated sediments, abundances subsequently increase and reach maximum levels at 2.6 m and 2.4 m respectively.

**Zone I:** At 2.4 m concentrations for dryland pollen suddenly double but *Eucalyptus* (15–18 µm),

Casuarinaceae (<28 µm), *Leptospermum*, Chenopodiaceae (all size classes), Sapindaceae, Gyrostemniaceae, Poaceae, Asteraceae and wetland taxa increase 4–6 times. This increase is not matched by similar increases in relative percentages for most taxa. Assuming pollen production is constant, this increase in concentrations imply a sudden reduction in deposition rates. However, *Eucalyptus* and Casuarinaceae double their representation but it is *Eucalyptus* that increases from 5% to 15% whilst Casuarinaceae only increases marginally and Chenopodiaceae declines 1.5 times.

At 2.3 m this spike is followed by a sudden reduction in pollen concentrations for a number of taxa. Again, these sudden changes are not matched by similar changes in representation and suggest an increase in the sedimentation rate rather than a hiatus in pollen deposition. A significantly large decline in Cupressaceae suggests an actual reduction in abundance.

There are major changes in the representation of certain taxa in this zone. *Eucalyptus* pollen percentages increase from 14% to 40% of the dryland pollen sum with *Eucalyptus* (15–18 µm) dominant, although a large proportion are eroded and *Eucalyptus* (>20 µm) increase. Casuarinaceae (both size classes) increase to 15% before declining to 10%, but it is the <28 µm size range that suddenly declines. Shrubby Myrtaceous taxa at 10% are increasingly dominated by *Melaleuca*. Herbaceous pollen, including Asteraceae (Tubuliflorae type) decrease steadily across this stratigraphic boundary and continue to decline to the top of the profile. Grasses are consistent at 10% throughout.

*Callitris* declines suddenly at 2.3 m and never recovers and, at 2.1 m, Chenopodiaceae has declined to ~6%. Sapindaceae and Gyrostemniaceae are absent from the record by 2.2 m. The Chenopodiaceae/*Allocasuarina* ratio peaks at 2.5 m.

There is greater complexity in taxa representing riparian indicator species. Concentrations are constant to 2.1 m but relative percentages increase to 7.5%. The increase is due mainly to *Dicksonia* spores with a lower proportion of eroded spores. The wetland taxa are dominated by *Myriophyllum*. However, abundances for all wetland taxa decline two-three fold above 2.4 m and *Persicaria*/*Polygonum* almost disappears above 2.5 m.

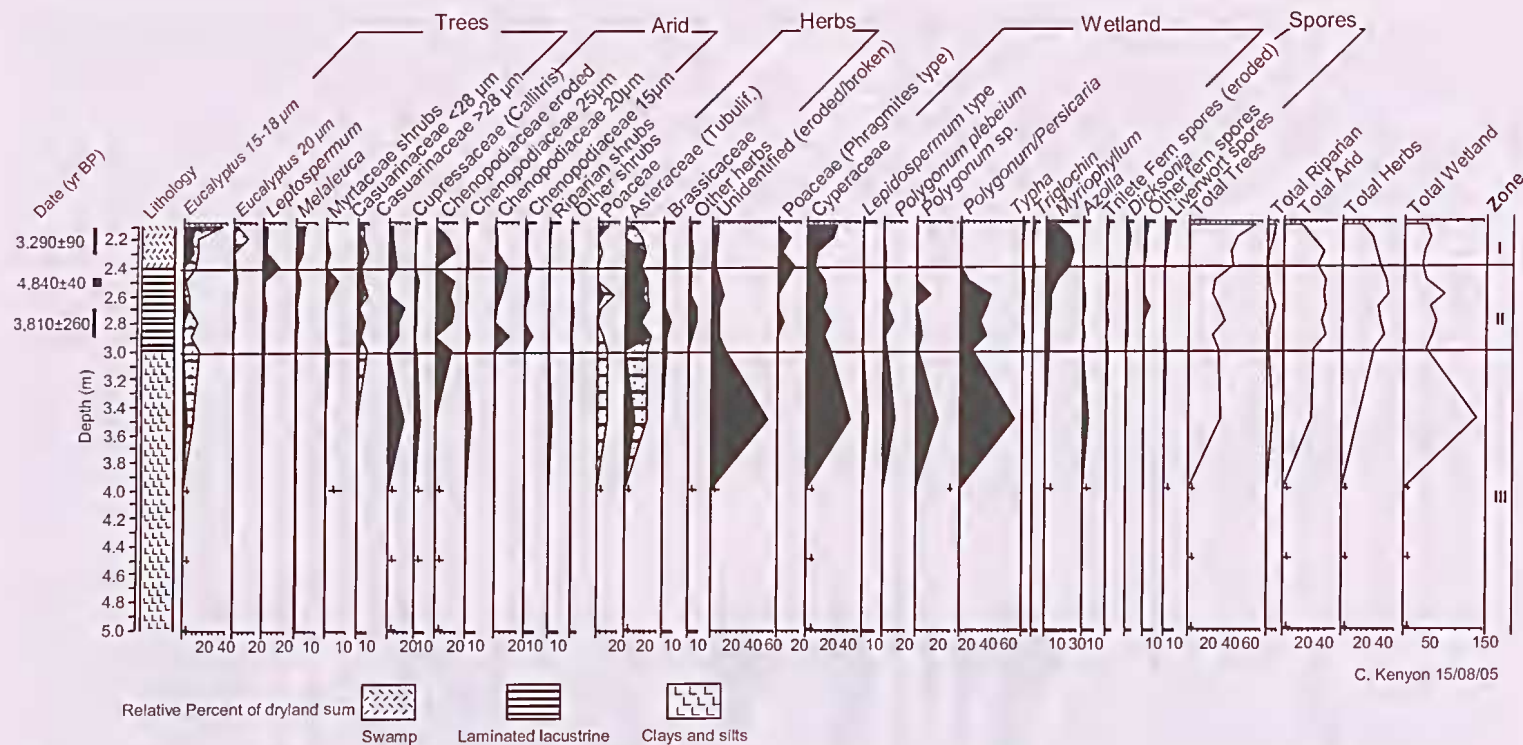


Fig. 3. Moirra Marshes pollen diagram: relative percentages of the dryland sum. Eroded pollen grains for each taxon are hatched. Note change of scale on X-axis for those taxa that are less than 10%.

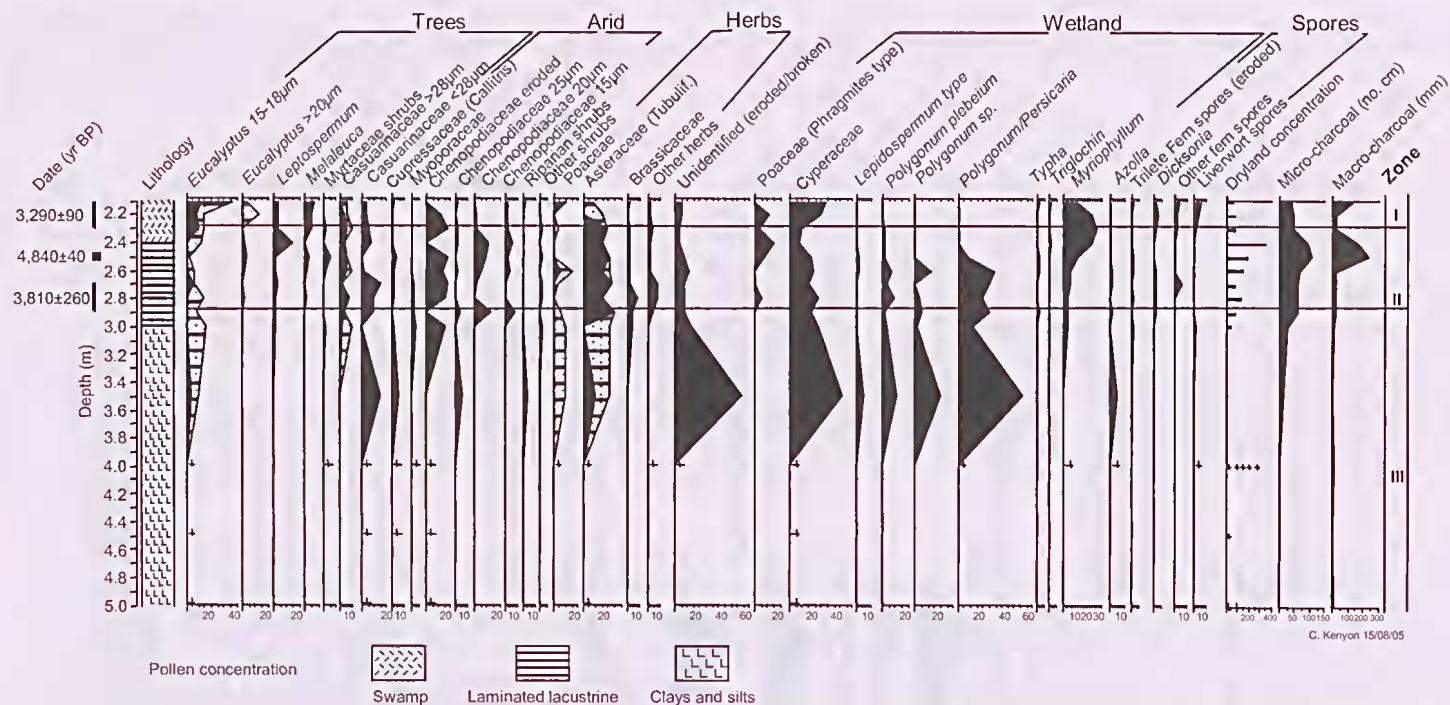


Fig. 4. Moirra Marshes pollen concentrations (no. grains cm<sup>-3</sup>). Diagram also includes the micro and macro-charcoal results.

### Charcoal analysis

**Surface samples.** In the surface sediments micro-charcoal area is similar at both sites being  $\sim 30 \text{ mm}^2 \text{ cm}^{-3}$ . Macro-charcoal concentrations are also similar at  $\sim 650 \text{ particles cm}^{-3}$  (Table 1).

**Moira Marshes.** Micro-charcoal area is low to 3.5 m but at 2.5 m there is a two-fold increase, comparable to that recorded in the pollen spectra (Fig. 4). Values then return to similar levels to those below 2.6 m and remain constant to the top of the profile. If, as for the pollen, changing deposition rates are responsible for these changes then there is a real increase in micro-charcoal particles above 2.4 m. Macro-charcoal particle concentrations are low to 3.0 m. Both increase rapidly and then remain constant to 2.6 m (Fig. 4). Concentrations increase 8 times to maximum values at 2.5 m and 2.4 m, then decrease by a similar amount before rising again. This represents a real increase in macro-charcoal particle concentrations at 2.5 and 2.4 m, then a decrease.

## DISCUSSION

### Pollen morphometry

Morphometric identification of *Eucalyptus* pollen to species level is difficult due to similarities in size and variability between and within species (Crowley 1994a; Chalson and Martin 1996). *Eucalyptus* pollen (15–18  $\mu\text{m}$ ) dominate the pollen rain and surface samples. The modern floodplain supports an extensive *Eucalyptus camaldulensis* Dehnh. forest and pollen of this size class is likely to be pre-dominantly from this species. *Eucalyptus* pollen grains with diameter  $>20 \mu\text{m}$  could represent a number of species and cannot be identified further. However, this size class is well represented in the modern pollen rain from the *Eucalyptus microcarpa* Maiden and *Eucalyptus melliodora* A. Cunn. ex Schauer box woodlands; all are likely candidates.

*Allocasuarina inchnmannii* R.T.Baker grows on the dry sandy soils of the Riverine Plains and within the Barmah-Millewa Forest (Chesterfield 1986). It grows where annual rainfall is 380–630 mm but can extend into regions of 225–300 mm (Doran and Hall 1981). This is most probably the species represented by Casuarinaceae pollen ( $>28 \mu\text{m}$ ). Historically, *Casuarina stricta* Aiton fringed the grass plains of northern Victoria with *Callinix glaucophylla*

(Hodgkinson 1856) and is common in southern Victoria: The pollen has an equatorial diameter of 35  $\mu\text{m}$  but these are rare in this pollen record. A number of species could be represented by the smaller Casuarinaceae pollen grains depending on climate, habitat and soil. *Allocasuarina cristata* F. Muell. and *Casuarina pauper* F. Muell. ex L.A.S. Johnson occur where rainfall is 175–275 mm per year and extend into the mid-Loddon region (Sargeant et al. 1979; Doran and Hall 1981) and either is a candidate for this pollen type.

Information on Chenopodiaceae pollen morphometry is sparse. However, *Chenopodium* (25  $\mu\text{m}$ ), *Einadia* (22  $\mu\text{m}$ ) and *Rhagodia* (15–17  $\mu\text{m}$ ) (Hopf et al. 2002) are all present in the regional salt-bush shrublands. It is not possible to take identification further.

Wetland taxa can provide quite specific information on local water levels and wetland nutrient status. *Polygonum* and *Persicaria* both grow on seasonally flooded, disturbed sites and along river banks flowering as water levels recede and they require variable temperature regimes to germinate. *Myriophyllum* has similar requirements (Ward 1992; Romanowski 1998) but is favoured by elevated phosphate levels (Roelofs et al. 1984). *Azolla* grows in association with nitrogen fixing blue-green algae common in nutrient-rich waters (Roelofs et al. 1984; Romanowski 1998).

### Mid-Holocene landscape reconstruction

**Floodplain hydrology and the river.** The colour of the basal gleyed clays is due to anaerobic reduction and the leaching of iron from the profile, resulting in very low magnetic susceptibility readings when sediments are saturated or inundated for long periods (Thompson and Oldfield 1986). Also, the very fine nature of the sediments indicates the Murray River was most probably entering the floodplain some distance away. On this low section of the floodplain was permanent, or near-permanent, shallow water, possibly a lake. However, the age of these sediments is unknown. In this period, fires occurred infrequently on the regional landscape and local fires were rare.

As suggested by the magnetic susceptibility record, sometime before 4,000 years BP the floodplain began to drain. The increase in fine and very fine sands at the same time imply that the Murray River, or a distributary channel, was having an

increasing influence on the site possibly forming a new channel as the lake drained to the south and the shoreline receded.

There was a return to permanent lake conditions ~4,000 years ago. However, the sudden increase in sand and the deposition of finely laminated sediments indicate the lake formed either as a terminal lake or within a floodplain depression and sediments were being deposited under an active regime of high seasonal flows from a nearby channel of the Murray River or a distributary channel. This situation is supported by the presence of riparian pollen from this time, as discussed below.

Approximately 3,000 years ago there was a decrease in river activity with lower flow and possibly less frequent flooding or the lake and channel were no longer directly connected. It is possible the lake had infilled to the level where only large flood events inundated the site or that seasonal inundation was shallower. It appears the site is sensitive to changes in regional groundwater and records increasing soil salinization, supporting the pollen evidence for maximum aridity at this time.

**Vegetation at 4,000 years.** A history of vegetation change is difficult to construct as the pollen records vegetation change on the regional lowland plains and from higher elevations of the upper catchment. At the same time the swamp vegetation reflects local hydrological conditions that are significantly impacted on by the Murray River. Approximately 4,000 years ago, at the time the second lake formed, the regional vegetation consisted of a mosaic of open Casuarinaeae and *Eucalyptus* woodlands or shrublands with *Callitris* and a number of arid-adapted shrubs also present. *Allocasuarina luehmannii* was a minor component of these woodlands and *Callitris* was no more abundant in the landscape than today. Grasses, Asteraceae and herbaceous vegetation dominated the regional woodland understorey and would have occurred on the drier regions of the adjacent floodplain. The regional vegetation was comparable to that of the modern semi-arid country to the north and west of the Barmah-Millewa Forest.

In this early lake phase *Eucalyptus camaldulensis* was rare at this site. Cyperaceae, as it is today, was an important component of the floodplain vegetation and seasonal inundation of the floodplain and possibly a river channel nearby is suggested by the presence of *Persicaria* and *Polygonum* (Romanowski 1998). It cannot be deduced from this study if the Moira grass Plains, characteristic of the

modern floodplain were present in the mid-Holocene.

**Regional soil salinization.** After ~4,000 years BP the semi-arid woodlands expanded; with Casuarinaeae <28  $\mu\text{m}$  expanding faster than *Eucalyptus* but *Allocasuarina luehmannii* contracted. This increasing aridity suggests *Allocasuarina cristata* or *Casuarina pauper* are represented by the smaller Casuarinaeae pollen grains and that annual precipitation was lower than 275 mm.

The Chenopodiaceae shrublands were always significantly more extensive than at present, and must have been growing close to the site. Even though Chenopodiaceae pollen is dispersed by wind the modern regional pollen rain, at less than 1%, reflects the distance of these saltbush shrublands from the site today. Beveridge (1889) described cooking mounds on the Lower Murray floodplains as having "a dense growth of giant salt-bush" and Broughton (1966) described saltbush extending right to the river bank in the Swan Hill region in the 1920s. It is possible that the sandhills of the Moira Marshes and the hinterland were similarly covered ~4,000 years ago.

The expansion of the chenopodiaceae shrublands and a corresponding decline first in Myoporaceae, then *Allocasuarina luehmannii*, *Allocasuarina cristata*, *Dodonaea* and *Callitris* at the Moira Marshes has also been recorded from other sites across south-eastern Australia and has been attributed to soil salinization driven by regional aridity between 4,000 and 2,000 years BP (Crowley 1994b; Gingeles et al. 2004). Crowley (1994a) used a level of 5% Chenopodiaceae pollen to indicate the occurrence of regional soil salinization. At this level Casuarinaeae pollen always declines in a pollen spectrum, so the Chenopodiaceae/Casuarinaeae ratio can be used as an indicator of soil salinization (Crowley 1994b). In the Moira Marshes record Chenopodiaceae pollen values of 15% were already present and Myoporaceae was declining when this second lake formed. Myoporaceae (*Myoporum montanum* and *M. parvifolium*) and *Allocasuarina luehmannii* growth is compromised at 5-6 dS/m whilst *Casuarina pauper* can tolerate levels to 10-15 dS/m whereas Chenopodiaceae are not affected until soil salinity reaches 20 dS/m (Doran and Hall 1981; Marear et al. 1995). From this, regional soil salinization reached levels of at least 5-6 dS/m and possibly 10-15 dS/m. Maximum salinization and, therefore aridity, was reached ~3,300 years BP based on the  $^{14}\text{C}$  dates, although it is likely to have been later. It is also possible these

taxa were affected by increased fire frequency, as discussed below.

*Upper catchment conditions.* A striking feature of this record is the sudden appearance, and increase, in taxa representing riparian (river corridor) and sub-alpine vegetation from ~4,000 years BP when lake conditions were established. Riparian indicators include *Dicksonia* and ground fern spores with *Tasmannia*, Lamiaceae and Rhamnaceae (*Pomaderris*) pollen. All are common components of modern cool wet gully vegetation at higher elevations. Together, they indicate cooler and wetter conditions at higher elevations in the catchment headwaters in the Eastern Highlands.

Pollen of riparian vegetation, in similar abundances, are present in the recent pollen spectra for the lower reaches of the Latrobe River (Kenyon et al. 1996) and for Lake Wellington in Gippsland (Grayson et al. 1998) where the pollen has been transported 50–60 kilometres along the rivers to the lake. In the Murray River catchment the nearest modern occurrence of this vegetation type is in the Ovens River catchment, on the slopes of Mount Buffalo, a distance of more than 200 river kilometres. Therefore, ~4,000 years ago, the closest riparian vegetation to the Moira Marshes must have extended downstream along the moist riparian corridor.

Approximately 3,000 years ago there was a major change in regional vegetation and in deposition rates at the site. First, the regional woodlands became more open and the understorey dominated by grasses. Second, at the time of maximum aridity sedimentation rates appear to have been low at a time when the river channel, or distributary and the lake may have been disconnected leaving the surface to dry for long periods. This was followed by an increase in deposition rates as swamp conditions developed and then prevailed at the site. A more abundant and diverse riparian vegetation suggests this vegetation community must have expanded its range down the Murray River Valley under continuing cool conditions and; a river channel was once again depositing sediment at the site, but as over-bank deposit under a lower energy system.

Regionally, Chenopodiaceae shrublands, *Allocasuarina cristata* and *Callitris* declined. Notably, *Allocasuarina luehmianii* was not affected to the same extent. *Eucalyptus camaldulensis* expanded again, growing along the river bank and possibly extending onto the now drier, but seasonally inundated, floodplain as open woodlands or forests. However, these woodlands were not as dense as the modern forest.

*Eucalyptus* replaced Causarinales toward the top of the sequence when, it appears conditions were ameliorating.

Myrtaceous shrubs, especially *Melaleuca*, increased considerably. On seasonally dry, swampy flats, Baird (1984) recorded massive *Melaleuca* regrowth on dry areas three years after a fire, but found that regeneration was slower on swampy areas. So, it is likely the increase in *Melaleuca* at the Moira Marshes was due to a seasonal drying of the site and to disturbance by fire. The floodplain supported a more extensive and diverse vegetation community dominated by Cyperaceae, but *Persicaria* and *Polygonum* were rapidly replaced by *Myriophyllum* as swampy and boggy conditions developed under fluctuating water levels and nutrient levels increased, possibly in response to the burning of the swamp surface. All of these taxa indicate variable climatic and variable hydrological conditions prevailed at the site (Romanowski 1998).

*Fire and vegetation.* Even though the incidence of fire on the landscape increased rapidly ~4,000 years ago it was still lower than for the modern regime and, although most likely due to wildfires, the activities of people in the landscape cannot be ruled out. This increase occurred under cooler but increasingly arid conditions possibly enhanced by greater variability associated with a strengthening of the ENSO cycle approximately 3,000 years ago (Stanley and De Deckker 2002; Gagan et al. 2004). These conditions would have provided the variation necessary for the build up of sufficient fuel loads to support a more frequent fire regime (Noble and Vines 1993). Local fires also increased but were still infrequent and possibly occurring on drier sections of the floodplain, or at the lake margins.

The peak in charcoal at the time of maximum aridity may be a real increase in fire frequency, but it more likely reflects a change in deposition rates, as discussed for the pollen. It is probable the regional fire regime at this time was depressed as fuel loads would have been low. Chenopodiaceae shrublands do not burn well and, as Noble and Vines (1993) noted, under arid conditions fire in semi-arid woodlands is dependent on sufficient grass to fuel the fire. Approximately 3,000 years ago when local swamp conditions were developing regional fires increased. The demise of *Callitris* and Myoporaceae was primarily due to soil salinization, but they may not have been able to regenerate under a more frequent fire regime. The result was a change in the composition and structure of the vegetation on the

adjacent Riverine Plains to more open woodlands or forests that were now dominated by *Eucalyptus* with more extensive grassy areas.

When swamp conditions developed there was an actual increase in the intensity of the local fire regime and fire-sensitive *Eucalyptus camaldulensis* (Chesterfield 1986) may have been disadvantaged for a short period in favour of other fire-tolerant species such as *Melaleuca* (Baird 1984; Nicol and Ganf 2000). This increase was followed by a period when local fires were infrequent at the same time as the sediments indicate the surface was dry and the river was not influencing the site. Fires immediately resumed at the site when the river was again close-by and swampy conditions again prevailed. It appears from this evidence that settlement at the site was dependent on the availability of both swamp and river resources.

#### *Mid-Holocene Climate at Moira Marshes*

Identifying the climate signal in this record is as complex as reconstructing the vegetation history, for the same reasons. Holocene climatic variability was not dramatic but the small variations evident in this record had significant effects on the vegetation, local hydrology and river flow. By 4,000 years ago conditions in the sub-alpine regions of the catchment to the south-east were becoming cooler and wetter. However, the pollen indicates the lowland Riverine Plain experienced a semi-arid climate that became increasingly arid to the extent that soil salinization developed. If cooler conditions accompanied the increasing aridity then reduced evaporation rates rather than increased precipitation can explain the wetter upper catchment conditions; that is, effective precipitation was high (Kershaw 1981). These increasingly drier and cooler conditions would have resulted in climatic variability with river flows exhibiting greater seasonality and transporting higher bedloads to the lowland reaches of the Murray River (Gingele and De Deckker submitted). Conditions appear to have ameliorated toward the top of the sequence.

#### *Regional comparisons*

Similar *Eucalyptus* and Casuarinaceae-dominated open semi-arid woodlands and chenopodiaceous shrublands have been recorded after ~4,000 years BP in northern western Victoria (Luly 1993; 1995;

Thomas et al. 2001) and on the Darling Anabranch (Cupper et al. 2000; Cupper 2005). A similar change in dominance from Casuarinaceae to *Eucalyptus* occurred after 5,000 years ago at Lake George (Singh et al. 1981; Singh and Geissler 1985). At Lake Tyrell (Luly 1993) and in the Darling Anabranch this occurred ~2,000 years BP (Cupper et al. 2000; Cupper 2005). Previous studies have shown regional aridity and soil salinization between 5,500 and 3,600 years ago. In western Victoria, lake levels were low (Bowler et al. 1976; Luly 1993; Crowley 1994a; Cupper, et al. 2000; Cupper 2005) and dune-building occurred in the Wagga Wagga district (Chen et al. 2002; Hesse and McTainsh 2003; Gingele et al. 2004). Costin (1972) identified a cool period in the Eastern Highlands between 3,250–1,540 years BP and Stanley and De Deckker (2002) found evidence in Eastern Highland dust deposits for climatic fluctuations in the mid-Holocene and a regional drying from about 5,500 to 3,600 years BP. River activity also reflects other studies where in eastern Australia (Cohen 2003) and on the Laehlan River (Kemp 1998) river activity increased between ~5,000 and 2,800 years BP, and Gingele and De Deckker (submitted) identified a pluvial pulse for the Murray River at 2,800 years BP. Maximum aridity in the region seems to have occurred ~2,000 years ago.

#### *Chronology*

The inversion of the two  $^{14}\text{C}$  dates is problematic. The thin laminations, and fine clay/silt sediments do not match the high deposition rates determined from the dates. The large number of burnt Cyperaceae seeds suggests they have remained *in situ* but have possibly been contaminated by the frequent wetting and drying cycles characteristic of this site. That they, and the beetle sclerite, have been transported from elsewhere on the floodplain cannot be ruled out. Due to this uncertainty this record indicates regional aridity occurred sometime between 4,000 and 3,000 years BP. However, it is possible the maximum aridity recorded by the pollen at 2.4 m is the same as that reported by Cupper (2005), and Luly (1993) across south-eastern Australia ~2,000 years BP. The basal age of the Moira Marshes sediments may be as old as ~6,000 to ~5,000 years BP.

*People in the landscape.* Although the increase in the frequency of fire in the region, approximately 4,000 years ago, was controlled by climate and variable environmental conditions it may also have been

influenced by human activity, as burning to clear the country and to maintain resources was a common practice (Jones 1969; Head 1988, 1994; Kohen 1996). The increase may reflect the movement of people into the moister riverine corridor and into the hinterland where the woodland resources potentially could be managed with fire and their open structure maintained. This is supported by the archaeological evidence that shows this movement occurred in the mid-to late-Holocene (Pardoe 1998), most likely in response to climatic instability and more dynamic environmental conditions. Rather than reflecting a population increase in the region, this movement is more likely to have been a response to the unpredictability of the changing environment. The hinterland environments were used seasonally, especially during winter when the floodplain was inundated for months at a time. For these reasons fire frequency would have been lower on the open plains than on the floodplain (Pardoe 1994).

Wetlands provide abundant food resources and as soon as these conditions prevailed they were managed using fire. It is also apparent from the record that river resources were important as the frequency of local fires was low when the river did not directly influence the site. At ~3,000 years BP there is a change from a climate dominated landscape to one maintained by fire. At the time Europeans arrived in the area in the 1840s, fire was certainly used to maintain open woodlands, clear reed beds and promote new growth (Curr 1883; Sturt 1899).

## CONCLUSIONS

The stratigraphic and pollen record indicate two possible lake phases for these sediments. The first, in the mid-Holocene at a time when the river entered the floodplain some distance away from the site; this lake eventually drained leaving a swampy floodplain. As the floodplain drained the river had an increasing effect on the site. A second permanent lake phase began ~4,000 years ago from the time the Murray River or a distributary channel directly influenced the site. This second lake infilled and swamp conditions prevailed from ~3,000 years ago.

In the mid-to-late-Holocene semi-arid open woodlands and extensive saltbush shrublands occurred regionally, but conditions were wet enough for these woodlands to expand. A change to increasing aridity and soil salinization eventually changed the composition of these woodlands. The floodplain

supported increasingly abundant and complex wetland vegetation communities while *Eucalyptus camaldulensis*, common on the modern floodplain today, was not as abundant. Temperatures in the upper catchment to the east were low and the Murray River corridor supported an extensive cool, moist riparian vegetation not present along the mid-Murray River today.

Initially, fire in the hinterland and on the floodplain was infrequent and dominated by climatic variability. From the time the river directly influenced the site and the second smaller lake formed, regional fire frequency increased significantly. This change in fire regime was most probably due to climatic variability but people moving onto the floodplain as the lake receded using fire for resource manipulation needs to be considered. Local fires did not increase dramatically until the lake began to dry and wetlands expanded ~3,000 years ago. The charcoal record and the interpreted history of fire demonstrates the opportunistic nature of occupation on the floodplain with people moving to a site when conditions provided abundant food resources and abandonment when resources were exhausted or conditions less favourable. People moved onto the floodplain and river banks, at least seasonally, and intensively managed the wetland resources using fire, altering the vegetation in the process. At this time the landscape became one that was increasingly managed for its resources, rather than being controlled by climate.

In the mid-Murray region it was a combination of cool humid conditions followed by increasing aridity, soil salinization and then anthropogenic fire that accounts for the increase, then decline in the open woodlands and in the ultimate decline in *Calitris* and *Allocasuarina* and the dominance of *Eucalyptus* ~2,000 to 3,000 years ago. The *Eucalyptus camaldulensis* forests of the modern forest most probably developed at this time.

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